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LASER SCANNING OF JUMA MACHIT'S COURTYARD AND DETAILED NUMERICAL STUDY ACCOUNTING FOR ROOF MEMBERS COMPROMISED BY TERMITE INFESTATION

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Abstract

This paper is focused on a study of Juma Machit's courtyard in Ichan Kala (Khiva, Uzbekistan). The courtyard represents an enclosed space surrounded by four walls that resulted in a trapezoidal overall plan view. It is fully covered by a roof supported by numerous lumber columns. The roof is constructed of lumber with a modern addition of a concrete layer on top of it. The relatively recent addition of the concrete layer creates additional structural demand on the room diaphragm. A detailed study of this demand is especially important now as there are obvious signs of a termite infestation in the lumber pieces. To address this issue, the courtyard was laser scanned from the inside and the outside, which allowed for the creation of a point cloud with high accuracy. A simplified numerical model of the roof was generated in order to study the effect of both static and dynamic loads. Based on the outcomes of this study, a more sophisticated model of the monument will be created that will include the brick walls, the columns, and the composite roof. Numerical simulations of the performance of this system under a combination of seismic loading and a snow load will be studied.

Keywords: Structural health monitoring, Non-destructive measurements, Termite infestation, Seismic loading, Snow loading, Laser scanning, Finite element modeling.

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1 INTRODUCTION

The objective of the paper is to study an effect of the ongoing termite infestation on the structural performance of the roof covering the courtyard of Juma Machit in Itchan Kala (Khiva, Uzbekistan). The roof is supported by the columns. Some of the columns are more than a thousand years old and were taken from the old Juma Machit which had been destroyed in a fire. During one of the recent reconstruction efforts a concrete layer was poured on top of the roof. As a result the roof was converted into a much heavier composite structural diaphragm consisting of lumber covered with a layer of concrete. To achieve the objective of the project Juma Machit was laser scanned to capture its geometry with high accuracy. The resulting point cloud was used for finite element modeling of the monument. The ongoing termite infestation was introduced by reducing the cross sections of the supporting roof members at the infestation locations.

2 LASER SCANNING

The courtyard of the mosque was previously laser scanned by a research team from Poland [1]. The study was limited to capturing the geometry of the monument's interior. The current research team expanded the research project. In the first phase of the project (2020), the exterior surface of the monument was scanned from eleven positions, the so-called stations [2]. A terrestrial laser scanner, C10 from Leica Geosystems [3], was utilized. In the summer of 2022, the second phase was conducted and the interior surface of the courtyard of the monument was scanned from six stations. These point clouds of the interior surface of the courtyard were stitched together with the point cloud of the exterior of the monument that had been collected earlier. The stitching was conducted in Cyclone [4]. The latter point cloud included the minaret and the interior walls of the courtyard. Laser scans conducted from the roof were added to the overall registration. As a result, the thickness of the wall, openings in the wall, column locations, and roof thickness can be obtained from the fully registered point cloud.

2.1 Overall point cloud

The complete registration that includes the point clouds collected in 2020 and 2022 is presented in Figure 1. It contains points of the exterior, interior, and roof surfaces.

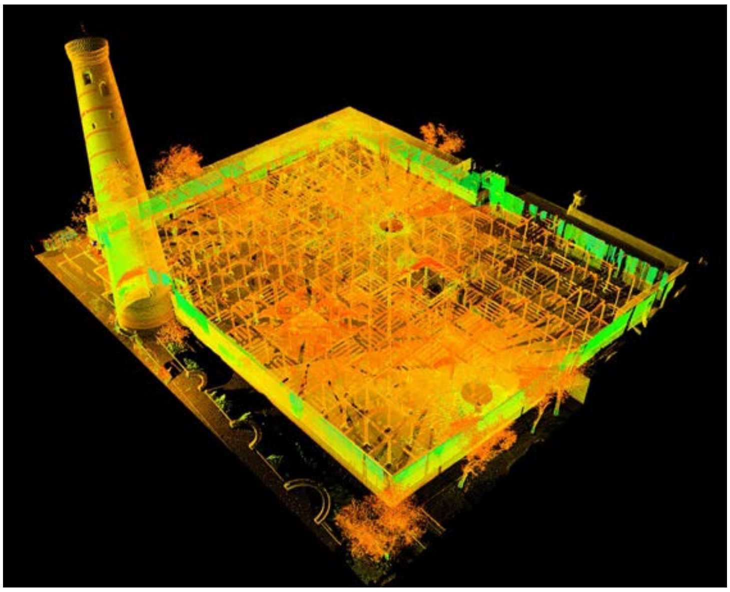


Figure 1: The complete registration containing exterior, interior, and roof surfaces.

It is worth noting that the 2020 phase of the project was conducted in December, so the roof surface was captured with a limited amount of snow.

The view of the courtyard is presented in Figure 2. The roof is supported by 213 columns which are located at the grid intersections as presented in Figure 3.

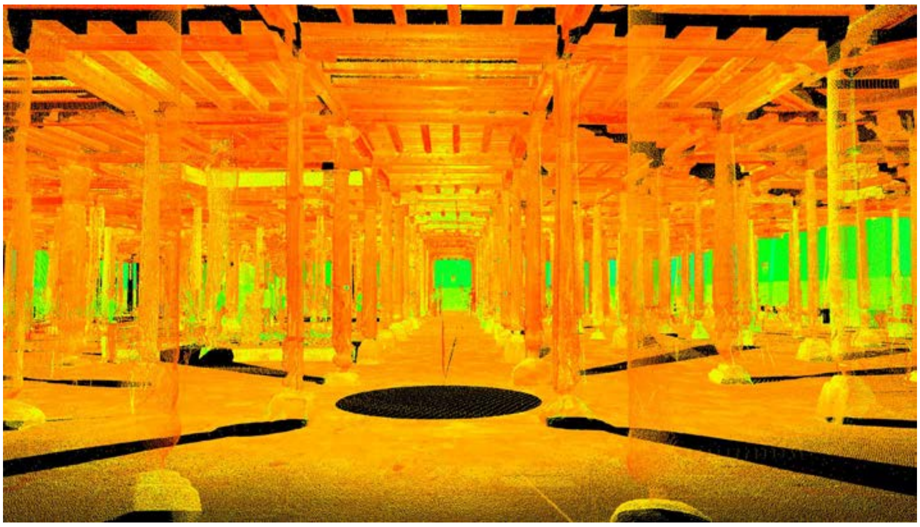


Figure 2: The courtyard's point cloud.

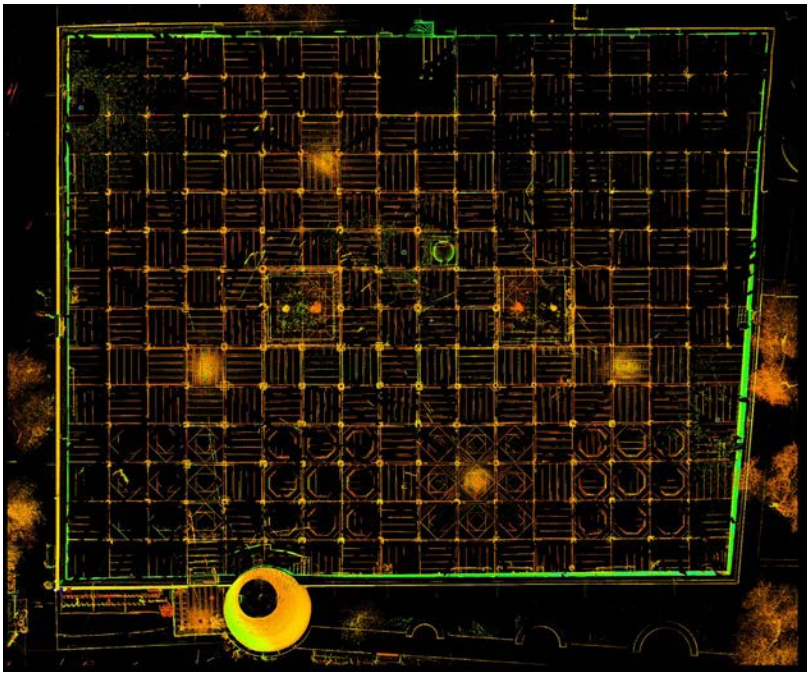


Figure 3: The supporting grid of the roof.

The processing of the fully registered point cloud was conducted in the Matlab environment. [5].

3 FINITE ELEMENT MODELING

The finite element modeling was conducted in the SAP2000 environment [6]. Some preliminary models were developed earlier [7]. Since the point cloud of the roof was incomplete the earlier models were limited to modeling the masonry structures, i.e., the walls and the minaret.

3.1 Selecting a column row to study

To assess the effect of the termite infestation the following approach was taken. It was assumed that the roof load is evenly distributed over the area of the roof. As a representative case for studying a load-carrying capacity, a row of columns along the width of the courtyard was selected as presented in Figure 4. This image shows the columns along the fourth row counted from the left of the image in Figure 3. It also contains half of the roof on each side of the column row in order to account for the roof's weight supported by these columns.

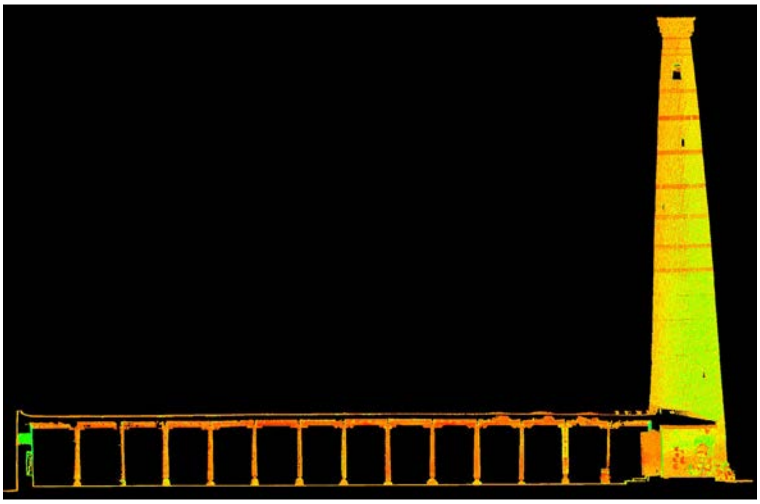


Figure 4: Typical row of columns.

3.2 Modeling of column row

The thickness of the roof was estimated from the point cloud as presented in Figure 5. As shown in the image, the roof thickness is close to 0.4 m. The bottom portion is constructed of round lumber pieces and it was assumed that their diameter does not exceed 0.1 m. Based on this assumption, the thickness of the concrete layer is close to 0.3 m.

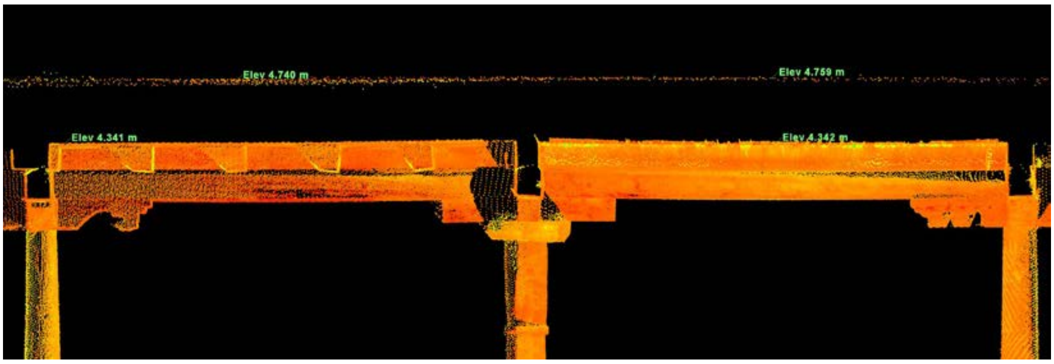


Figure 4: Typical row of columns.

The modeling of this part of the roof was conducted in SAP2000 and it is presented in Figure 5.

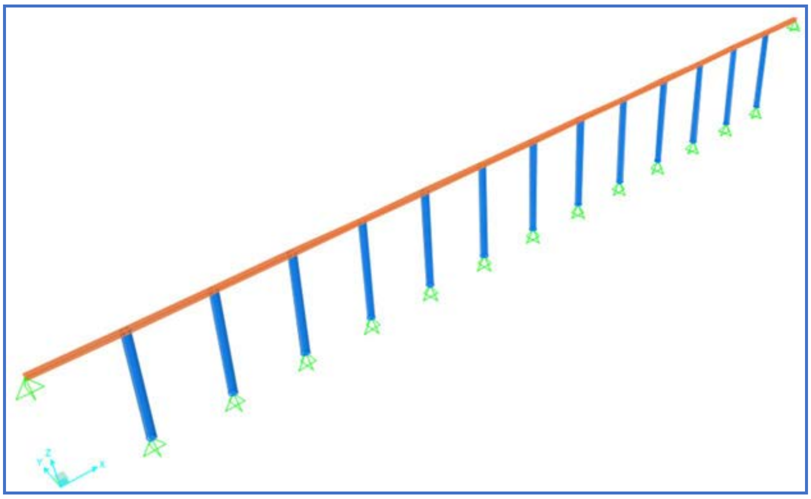


Figure 5: Model of column row.

3.3 Static analysis

A few finite element models were generated. The original roof cover of Juma Machit was likely done by laying a thick layer of wet clay on top of the wooden ceiling. This construction approach was commonly. Hence, Model A was generated for the case of the clay cover. Model B was generated for the case of the concrete cover. Model C represents the case with snow on top of the concrete layer. Model D corresponds to the case without any layer above the wooden ceiling. A summary of the results obtained for the static dead load analysis is presented in Table 1.

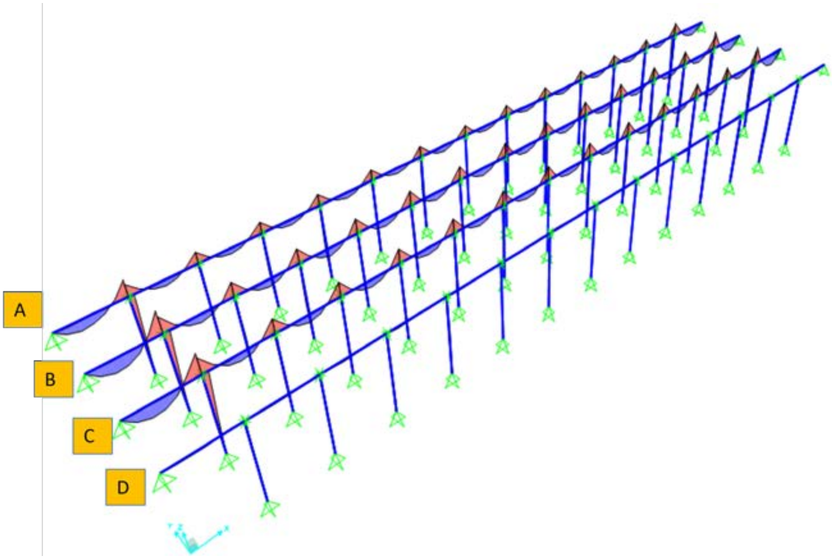


Figure 6: Four models with different load combinations on top of wooden ceiling.

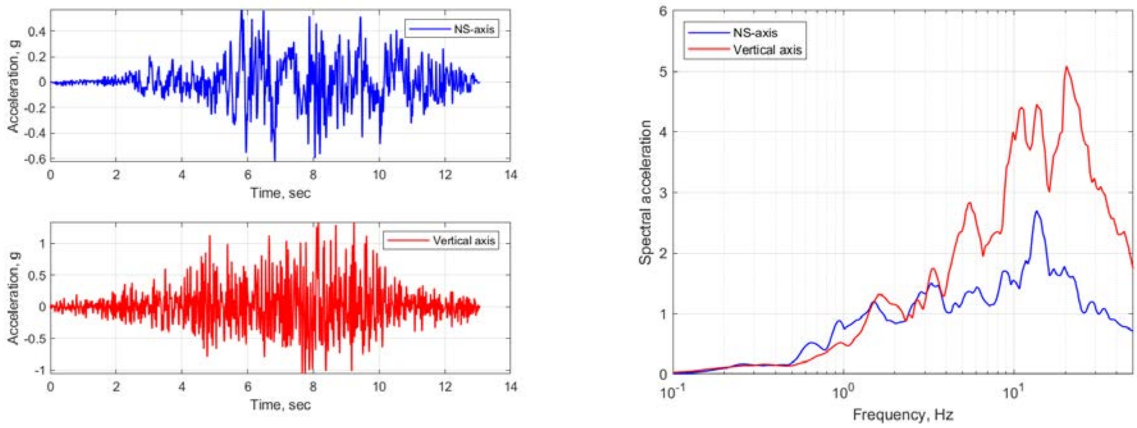
Model	Description	Percentage to Model A
A	Clay	100%
B	Concrete	128%
C	Concrete+snow	131%

Table 1: Maximum static moments in the beams normalized to that for Model A.

As presented in Table 1, the modern replacement of the clay layer with the concrete layer most likely increased the bending moments in the beams by about 28%. When accounted for the snow load the moments increased to about 31%. For the snow load, it was assumed that the roof has a uniform layer of snow that is 0.3 m thick, which is a common amount of snow for this region of Uzbekistan.

3.4 Dynamic analysis

A historic record obtained during the 1976 Gazli earthquake in Uzbekistan was utilized for the dynamic analysis. All models described above were excited with this earthquake record. Only two components of this record were used as presented in Figure 7. Note that the “NS-axis” stands for the north-south axis. Figure 7a shows the acceleration time histories. Figure 7b shows spectral accelerations which indicate that the spectral demand in the vertical direction was about two times greater than the demand in the horizontal direction.



a) Acceleration time histories   b) Spectral accelerations

Figure 7: Four models with different load combinations on top of wooden ceiling: dynamic analysis.

The results of the dynamic analysis are presented in Figure 8 which are summarized in Table 2.

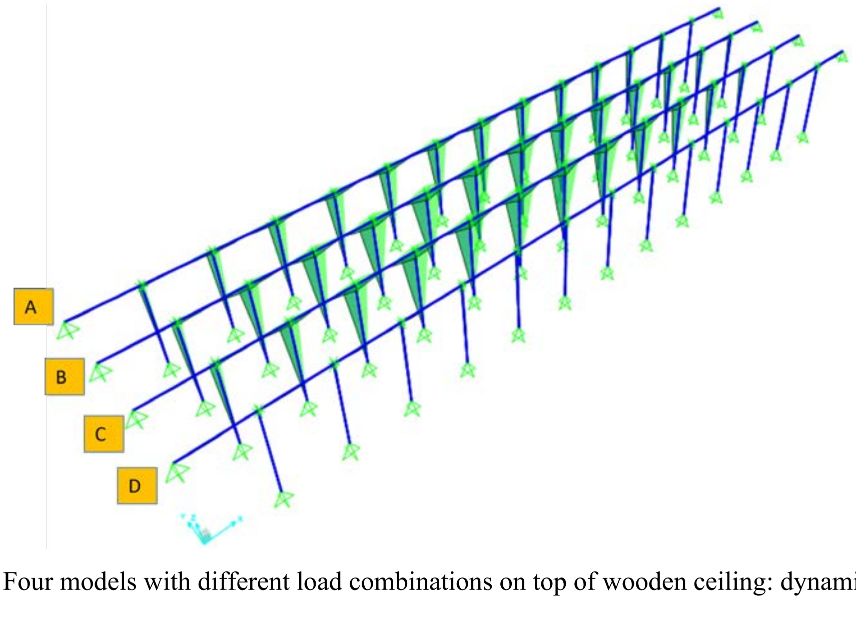


Figure 8: Four models with different load combinations on top of wooden ceiling: dynamic analysis.

Model	Description	Percentage to Model A
A	Clay	100%
B	Concrete	139%
C	Concrete+snow	145%

Table 2: Maximum dynamic moments in the beams normalized to that for Model A.

As presented in Table 2, the modern replacement of the clay layer with a concrete layer- most likely increased the bending moments in beams by about 39%. When accounting for the snow load the moments increased to about 45%.

3.5 Sagging analysis and accounting for termite infestation

Analysis of the point cloud indicates that a few beams had noticeable sagging. A typical case of beam sagging along with other roof elements is shown in Figure 9.

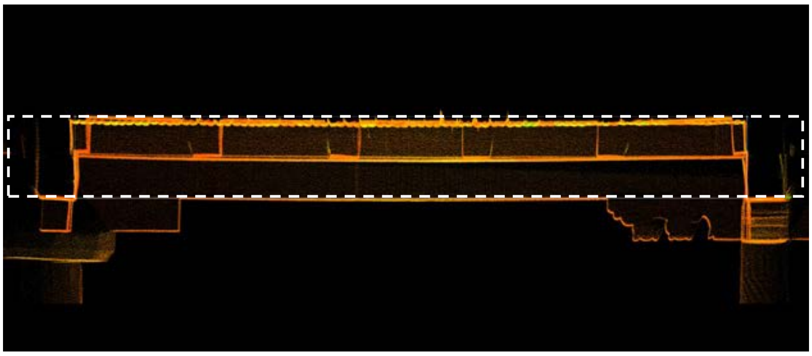
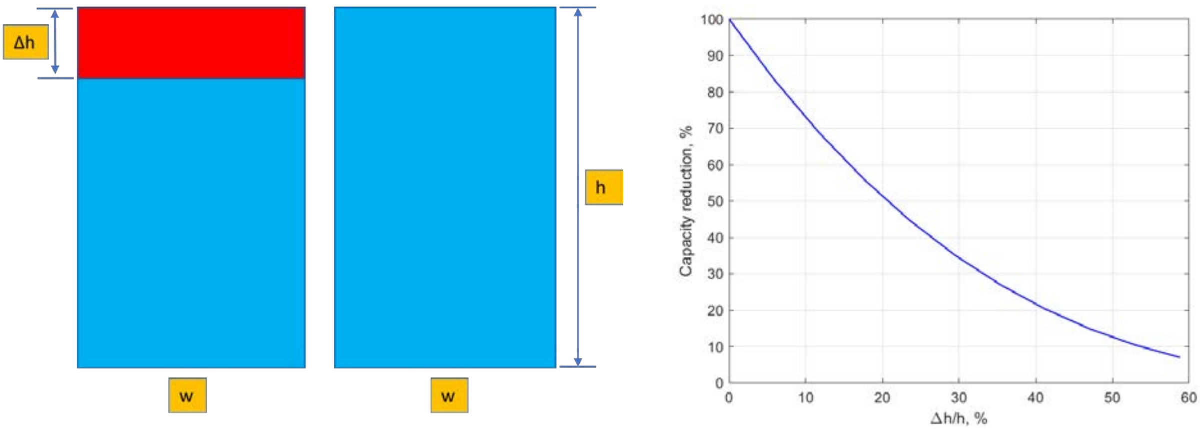


Figure 9: Sagging of the beam and roof elements (a reference straight block shown in white).

When a beam is affected by a termite infestation a load-carrying capacity of the beam in bending can be reduced due to the reduction of a cross-sectional area that will resist bending. A simple case is presented in Figure 10a which shows a cross-section of the beam before (right) and after infestation (left). The area compromised by the termite infestation is shown in red. The change in capacity of carrying the bending load is presented in Figure 10b.



a) Beam's cross section before (right) and after (left) infestation: red indicates affected area

b) Capacity reduction: ratio of stresses after to that before the infestation

Figure 10: Simplified case of termite infestation and reduction in the beam's load-carrying capacity.

The results provided in Figure 10b are based on the well-known calculation of the bending stresses, σ (see, [8] as an example):

$$\sigma = M/(EI) \tag{1}$$

Where M is the bending moment, E is the Young modulus of the lumber and I is the moment of inertia of the beam's cross section.

The moment of inertia for the rectangular cross section is estimated by a commonly known expression (w is the width and h is the depth of the cross section as shown in Figure 10a):

$$I = wh\hat{}3/12 \tag{2}$$

For the case in which a portion of the cross section with a depth of Δh is affected by termite infestation the reduction of the stress capacity in bending can be computed by the following expression:

$$Reduction\ in\ stress\ capacity = (1 - (\Delta h/h)\hat{}3) \tag{3}$$

The expression (3) is presented in a graphical form in Figure 10b. The plot shows that the bending capacity of the beams drops dramatically when the depth of the compromised area increases. For example, when the compromised area is half of the original depth of the beam the load-carrying capacity drops to less than 15% of the capacity before infestation.

4 CONCLUSIONS

The paper is the first attempt in studying the stability of the roof in the Juma Machit monument (Khiva, Uzbekistan). The courtyard of the minaret was scanned from the outside, inside, and top of the roof. As a result an accurate point cloud of the monument including its roof and all supporting elements was captured. As a starting point of this investigation a simple numerical model was generated from the collected point cloud. The numerical model was investigated under static loading. The recent addition of a thick concrete layer to the top of the roof was studied through FE modeling. It was assumed that the top layer of the roof was constructed of clay. This model was compared to an FE model with the top layer built of concrete. It was shown that the concrete layer increased the demand for the beams by about 31% for static dead load analysis. The same models were subjected to dynamic loading that replicate the ground motions recorded during the 1976 Gazli earthquake. It was shown that the concrete layer increased the demand on the beams by about 45% in a time history analysis. The large demand can result in significantly larger stresses in the areas where the supporting beams are affected by the termite infestation. In the next phase of the project a detailed finite element model will be developed that will investigate the impact of both static and dynamic loadings. A reduced cross section will be introduced at the locations with a severe termite infestation. The results of the numerical simulations will be used for developing restoration strategies.

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